A relativistic shock scenario for extreme-TeV blazars.

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abstract

The multi-wavelength emission from extreme-TeV blazars [Biteau et al. 2020] is difficult to interpret with standard emission models. Large values of the minimum electron Lorentz factor and unusually low values of the magnetization seem required.

We propose a scenario where protons and electrons are co-accelerated on internal or recollimation shocks inside the relativistic jet. In this situation, energy transfer from the protons to the electrons leads naturally to a high minimum Lorentz factor for the latter, while low magnetization is a necessary condition for particle acceleration.

Values of the magnetic field strength of a few mG and minimum electron Lorentz factors of 10^3 to 10^4, required to provide a satisfactory description of the observed spectral energy distributions, result here from first principles.

While acceleration on a single shock is sufficient to reproduce the emission of most of the handful of extreme-TeV sources we have examined, re-acceleration on a second shock appears needed for those objects with the hardest gamma-ray spectra, 1ES 0229+200 and 1ES 1101-232.

e^- p^+ co-acceleration on relativistic shocks

In relativistic electron-ion shocks, most of the energy that enters the shock front is carried by the ions, but a fraction of it is given to the electrons, which are thereby preheated up to a fraction of equipartition.

In the weakly magnetized limit, one promising scenario to explain this effect is collisionless Joule heating of electrons [Lemoine et al. 2019, Vanthieghem et al. 2021]. In phenomenological models of GRB afterglows, the electron energy fraction is almost always found to be within a factor of a few from the ion energy fraction [Kumar & Zhang 2015]. At large shock velocities, and small magnetizations, PIC simulations [Sironi & Spitkovsky 2011, Sironi, Spitkovsky, & Arons 2013] find that the fraction of energy stored in electrons increases up to half of that in the ions, implying $k_B T_e \sim 0.1 \gamma_{\rm sh} m_p c^2$. For mildly relativistic shock acceleration,

$$\gamma_{p,min} \sim \gamma_{\rm sh} \quad , \quad \gamma_{e,min} \sim 600 \gamma_{\rm sh} . \tag{1}$$

The acceleration timescale is given by $t_{\rm acc} \simeq t_{\rm scatt}$ in relativistic shocks, where $t_{\rm scatt}$ denotes the scattering timescale. For scattering in microturbulence, this constraint can be reexpressed as a function of magnetization σ:

$$\gamma_{e|p,{\rm max}} \lesssim \frac{\gamma_{e|p,{\rm min}}}{\sqrt{\sigma}} \tag{2}$$

Here $\sigma << 10^{-2}$ is required for efficient shock acceleration.

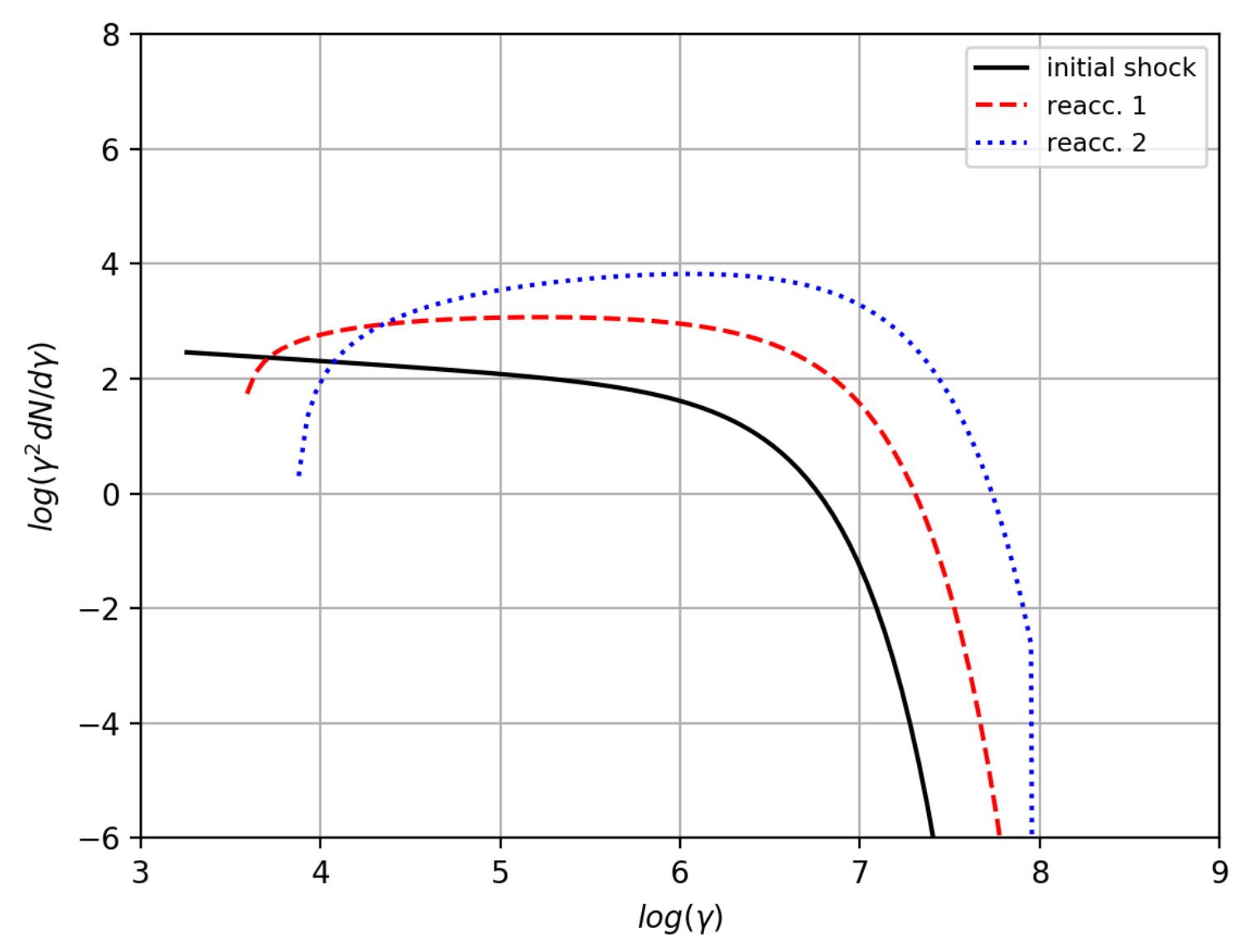
To arrive at acceptable solutions, we allow for an enhancement of the magnetization in the emission region σ_{rad} compared to the value of σ upstream of the shock, as is observed in PIC simulations.

re-acceleration scenario

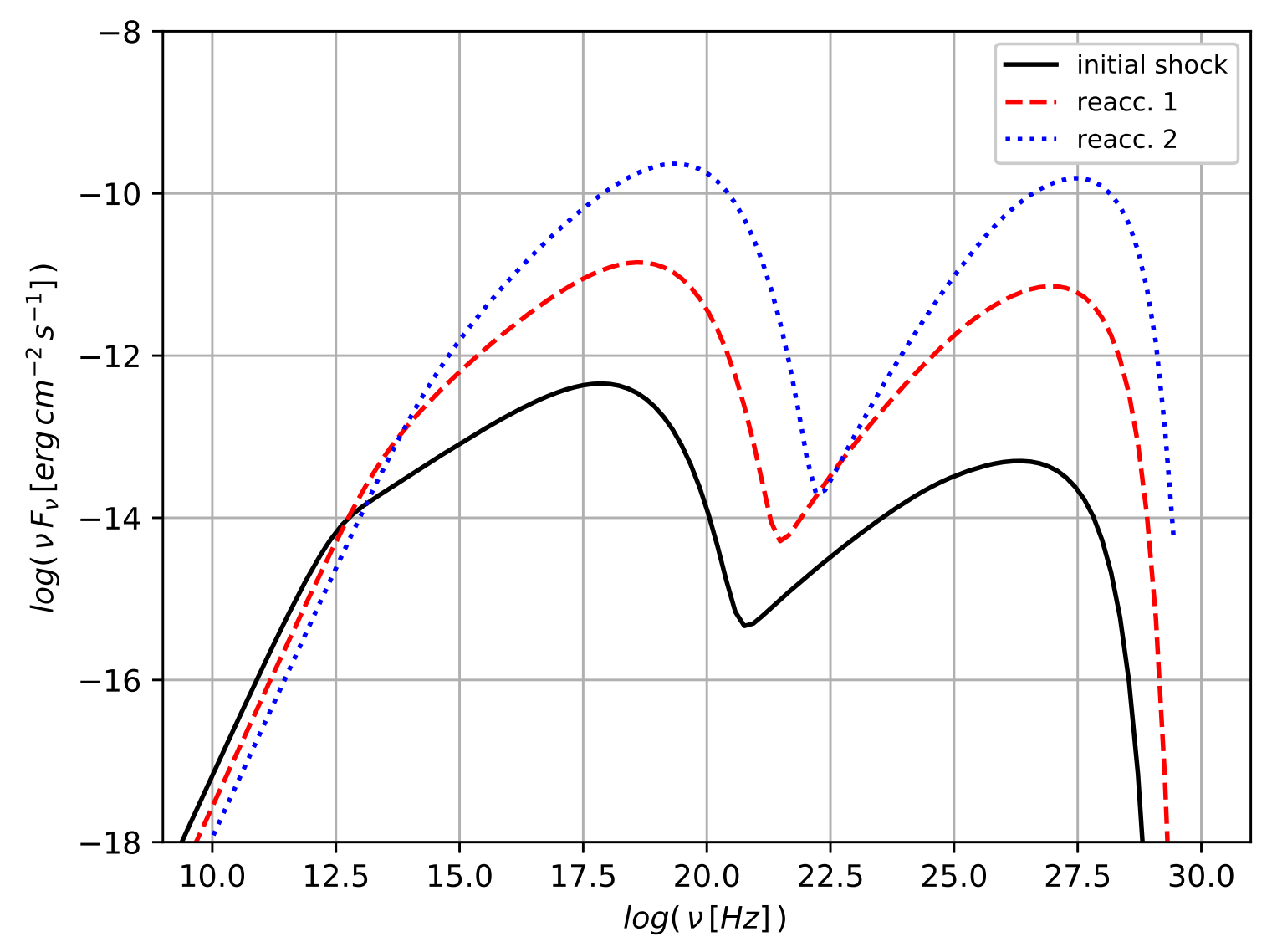
As recollimation (or, more generally, standing) shocks may come in series of shock fronts in the jets of radio-galaxies and blazars, we must consider the possibility that the radiating blob undergoes multiple episodes of shock acceleration, which may substantially modify the spectrum of accelerated particles. If one can neglect cooling effects in-between successive shocks, the particle distribution after n shock crossings is then given by [Achterberg 1990, Schneider 1993]

$$\frac{{\rm d}N^{(n)}_{>}}{{\rm d}\gamma_{>}} = \frac{(s-1)^{n+1}}{n!\, g^n\, \gamma_{\rm min}} \left(\frac{\gamma_{>}}{g^n\, \gamma_{\rm min}}\right)^{-s} \ln\left(\frac{\gamma_{>}}{g^n\, \gamma_{\rm min}}\right)^{n} . \tag{4}$$

Here, g represents the energy gain from one shock to the next, $g \simeq \Gamma_{\rm rel}^{2/3}$, depending only on the relative Lorentz factor between pre-shock and post-shock flows. This has two important consequences: (1) the spectrum hardens because of reacceleration; (2) the effective injection Lorentz factor, which was $\gamma_{\rm min}$ at the first shock, has become $g^n \gamma_{\rm min}$ at the $n-$th shock. The hardening is stronger at momenta close to the effective injection momentum than at high energy. To make connection with the model parameters, $\gamma_{e,{\rm min}}$ is now given by $g^n\, \gamma_{e,{\rm min}}$, with $\gamma_{e,{\rm min}} \simeq 600 \gamma_{\rm sh}$.



Particle spectra for the same electron and proton population after the initial shock acceleration and after a first (red) and second (blue) re-acceleration on successive shocks.



Observed SEDs due to SSC emission from the particle populations shown on the left after an initial shock acceleration and two re-accelerations. The SEDs correspond to a source at redshift $z = 0.14$ with $\delta = 50$.

model setup

Our model is based on a standard one-zone lepto-hadronic scenario with the following parameters: the strength of the uniform magnetic field (B), the size of the spherical emission region (R), its Doppler factor (δ), the minimum and maximum Lorentz factors of the electron and proton distributions ($\gamma_{\rm e|p,min}$, $\gamma_{\rm e|p,max}$), a single index of the particle distributions ($s \sim 2.2$) and their normalizations ($K_{\rm e|p}$).

For low magnetizations, radiative electron cooling and emission from protons can be neglected. Spectral Energy Distributions (SEDs) of extreme-TeV blazars are well represented with the synchrotron self-Compton (SSC) emission of a power-law electron distribution with an exponential cutoff:

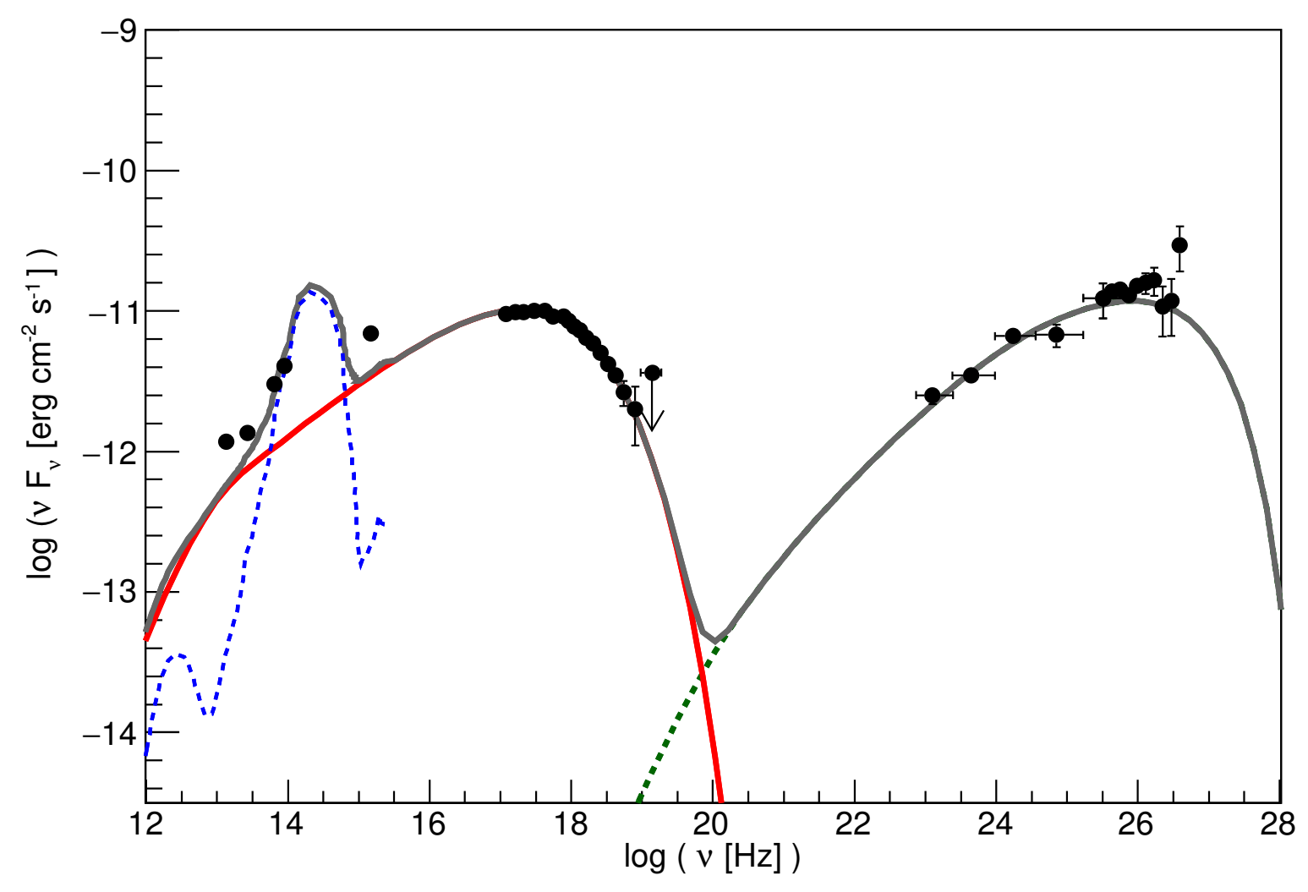
$$\frac{dN_e}{d\gamma} = K_e \gamma^{-s}\, e^{-\gamma/\gamma_{\rm e,max}} . \tag{3}$$

We assume co-acceleration of electrons and protons, both following the same power law, but with different ranges of Lorentz factors (cf. Equ. 1 and 2).

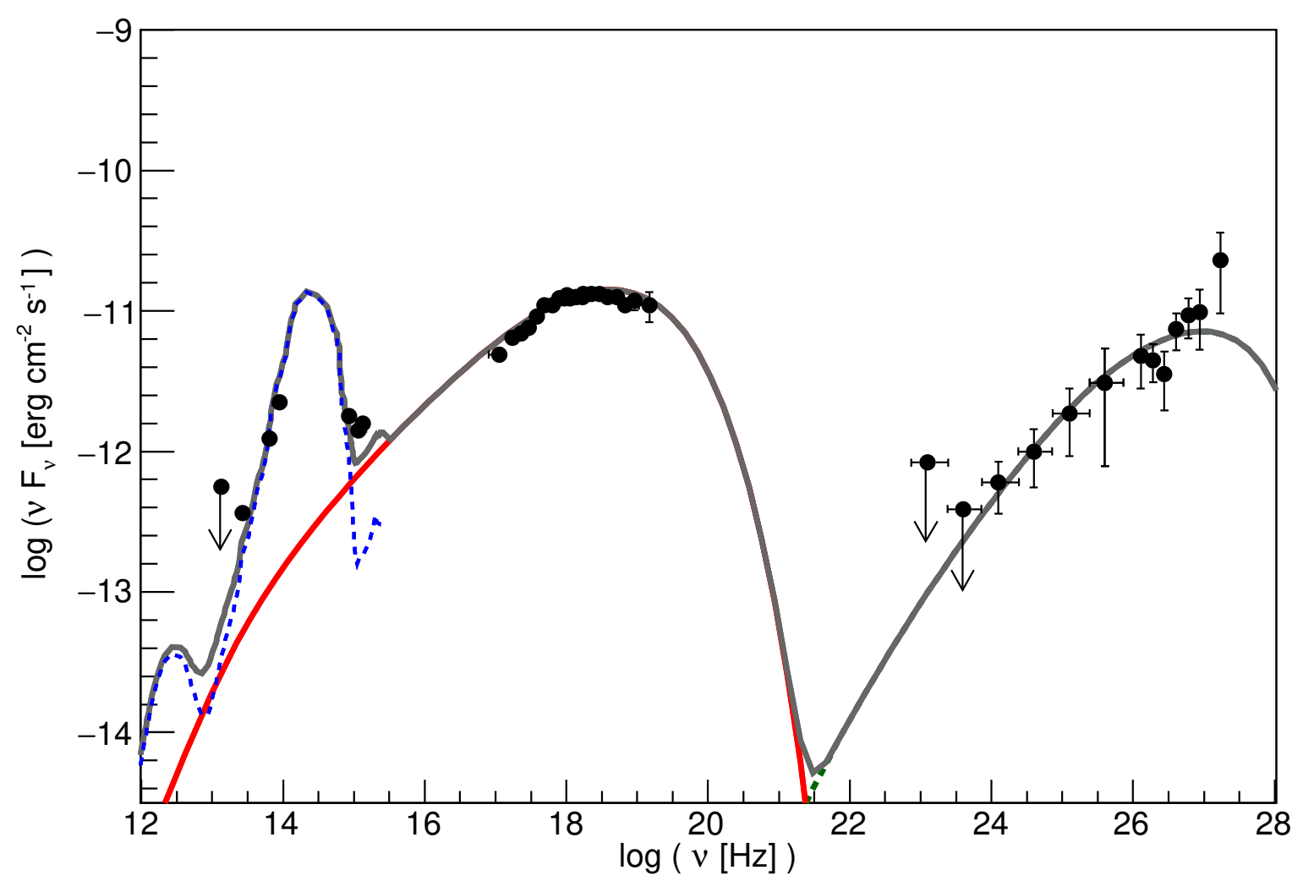
A first estimate of the model parameters for a give SED is based on the relations given by [Tavecchio, Maraschi, & Ghisellini 1998] in the Klein-Nishima regime:

For a given value of δ, $\gamma_{e,{\rm max}}$ can be determined from the Inverse Compton peak frequency. Then the strength of B in the emission region can be estimated from the value of the synchrotron peak frequency. Then $\gamma_{e,{\rm min}}$ is constrained by the SED and σ is determined following Equ. 2. Assuming a proton-electron plasma with $n_e = n_p$, the normalization K_e is related to $\sigma = u_B/u_p$.

application to extreme blazars



SSC model for the SED of 1ES 1218+304 for acceleration on a single shock.



SSC model for the SED of 1ES 0229+200 for re-acceleration on a second shock.

	1ES 0229+200	1ES 1218+304
δ	50	60
$R_{\rm src}$ [10^{16}cm]	1.3	1.4
B [mG]	4.4	8.4
σ	3.7×10^{-7}	1.3×10^{-5}
$\sigma_{\rm rad}$	1.0×10^{-4}	1.4×10^{-4}
$\gamma_{e,{\rm min}}$	1.8×10^{3}	1.8×10^{3}
$\gamma_{e,{\rm max}}$	2.9×10^{6}	5.0×10^{5}
n_e [cm^{-3}]	4.2×10^{-2}	1.3

Data points from [Costamante et al. 2018].

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